REPORT No. 658

TESTS OF TWO FULL-SCALE PROPELLERS WITH DIFFERENT PITCH DISTRIBUTIONS, AT BLADE ANGLES UP TO 60°

By David Biermann and Edwin P. Hartman

SUMMARY

Two 3-blade 10-foot propellers were operated in front of a liquid-cooled engine nacelle. The propellers differed only in pitch distribution; one had normal distribution (nearly constant pitch for a blade angle of 15° at 0.75 radius), and the other had the pitch of the tip sections decreased with respect to that for the shank sections (blade angle of 35° for nearly constant pitch distribution). Propeller blade angles at 0.75R from 15° to 60°, corresponding to design speeds up to 500 miles per hour, were investigated.

The results indicated that the propulsive efficiency at a blade angle of 60° was about 9 percent less than the maximum value of 86 percent, which occurred at a blade angle of about 30°. The efficiency at a blade angle of 60° was increased about 7 percent by correcting for the effect of a spinner and, at a blade angle of 30°, about 3 percent. The peak efficiencies for the propeller having the washed-out pitch distribution were slightly less than for the normal propeller but the take-off efficiency was generally higher.

INTRODUCTION

Tests of full-scale propellers made at the N. A. C. A. have previously been confined to blade angles at 0.75R of 45° and less, which correspond to airplane speeds below 400 miles per hour for tip speeds of 1,000 feet per second. If lower tip speeds were employed to reduce compressibility losses for the take-off, the corresponding air speeds would be even lower. In view of the trend toward greater airplane speed, it is obviously desirable to have available propeller data covering all contemplated design conditions for a period of several years. The present investigation extends the blade-angle range to 60°, which corresponds to a design air speed of about 500 miles per hour for a tip speed of 1,000 feet per second or to 400 miles per hour for a tip speed of 800 feet per second. (See fig. 1.)

One of the propellers investigated was designed with a nearly uniform pitch distribution for a blade-angle setting of about 15° at the 0.75 radius. When the blades are set at higher angles, the pitch increases with the radius. Tests of model propellers (reference 1) have shown that, for a tractor propeller, a radial increase in pitch near the hub is beneficial but that a further radial increase in pitch near the tips is harmful. As the present investigation was to cover a wide range of blade angles, it was believed that the pitch distribution of the test blades would not be entirely satisfactory for all blade angles. The program was therefore laid out to include tests with the pitch maintained constant over the outer halves of the blades for blade angles of 15°, 25°, and 35° and also to include tests showing

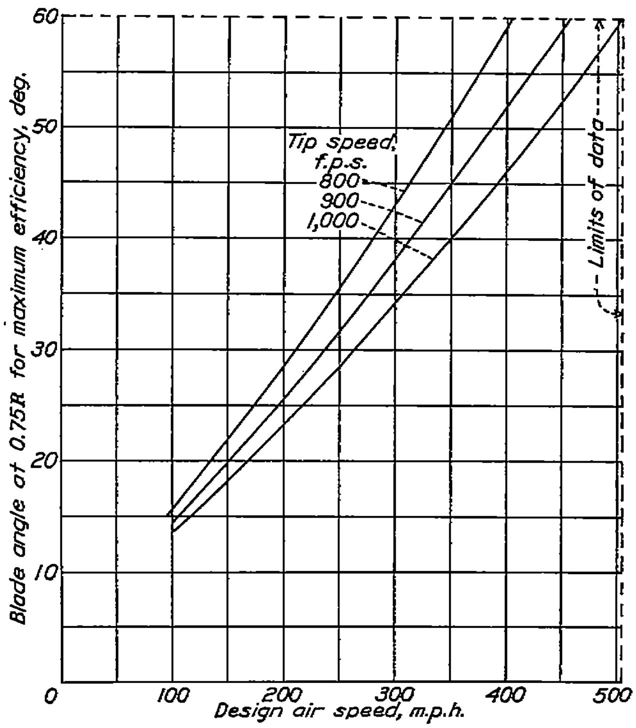

FIGURE 1.—Design conditions for maximum efficiency. Propeller 5868-9 with spinner.

the effects of a radial engine nacelle and of a liquid-cooled engine nacelle. Unfortunately, some of the results were in error owing to breakage in the balance system; only the results for the two extreme pitch distributions with the liquid-cooled engine nacelle are therefore reported.

In view of the fact that propeller spinners are very beneficial for high-speed airplanes equipped with liquid-cooled engine nacelles, the results of the tests of the propeller with the standard pitch distribution at a blade angle of 15° are also given for the spinner condition.

APPARATUS AND METHODS

The propeller-research tunnel has been modified since the description of reference 2 was written to the extent of installing an electric motor to drive the tunnel propeller and of replacing the balance with a more modern one capable of simultaneously recording all the forces.

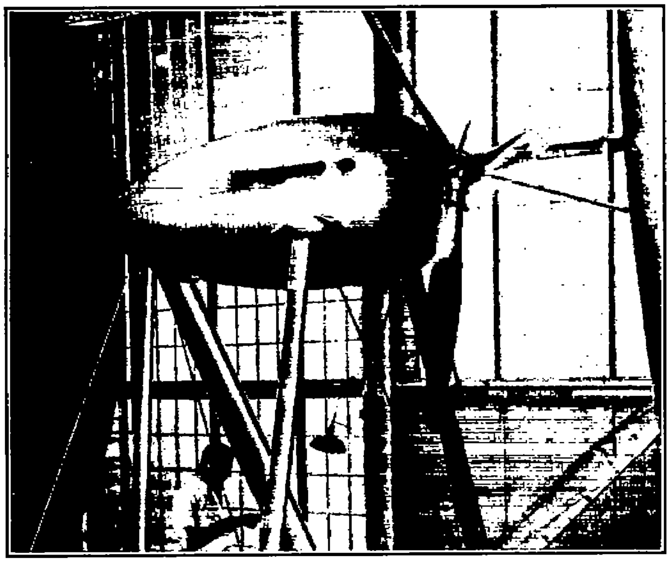

FIGURE 2.—The propeller test set-up with liquid-cooled engine nacelle.

A 600-horsepower Curtiss Conqueror engine (GIV-1570) was used to drive the test propellers. The engine was mounted in a cradle dynamometer free to rotate about an axis parallel to the propeller axis and located at one side of the engine. The torque reaction was transmitted from the other side of the engine to recording scales located on the floor of the test chamber. The propeller speed was measured by a calibrated electric tachometer.

FIGURE 3.—Liquid-cooled engine nacelle with spinner.

The liquid-cooled engine nacelle, shown in figure 2, is oval in cross section, 43 inches in height, 38 inches in width, and 126 inches in length. A detailed drawing of the liquid-cooled and the radial engine nacelle is given in figure 1 of reference 3. Figure 3 shows the liquid-cooled engine nacelle and the propeller fitted with the spinner.

The two propellers tested in this investigation are 3-blade 10-foot-diameter propellers of Clark Y section and are identical except for pitch distribution. Propeller 5868-9 is a Navy Bureau of Aeronautics design having a fairly uniform pitch distribution over the outer half of the blades when set 15° at 0.75R. The 5868-X_3 propeller has a uniform pitch distribution over the outer half of the blades when set 35°. The plan form and the blade-form curves are given in figure 4 and a comparison of the pitch distributions is given in figure 5.

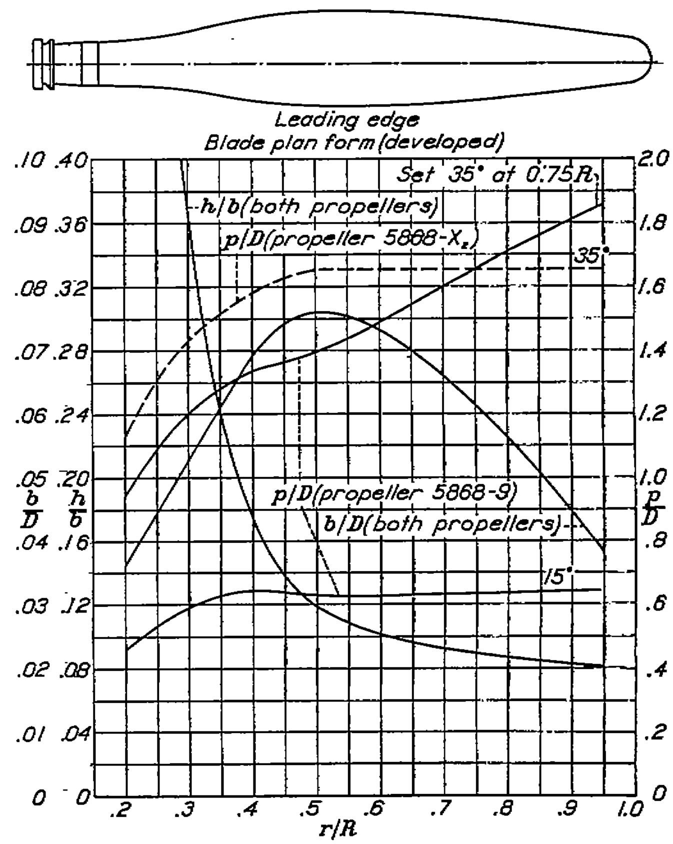

FIGURE 4.—Plan form and blade-form curves for propellers 5868-9 and 5868-X_3. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch.

The method of testing in the propeller-research tunnel consists in maintaining the propeller speed constant and increasing the tunnel speed in steps up to the maximum value of 115 miles per hour. Higher values of V/nD are obtained by reducing the engine speed until zero thrust is reached. The tests were run at tip speeds of 525 feet per second and less to avoid complications arising from compressibility. The standard initial testing propeller speed of 1,000 r. p. m. could not be maintained for the higher blade-angle settings owing to the limitation of engine power. The following schedule was adhered to:

Propeller speeds for tunnel speeds below 115 miles per hour

Blade angle (deg.)	Initial propeller speed (r. p. m.)	Blade angle (deg.)	Initial propeller speed (r. p. m.)
15	1, 000	40	700
20	1, 000	45	700
25	800	50	650
30	800	55	600
35	800	60	560

For V/nD values higher than can be obtained from the foregoing schedule, the approximate test propeller speed may be computed from the relation $\text{r. p. m.}=\frac{K}{V/nD}$ where K=1,000 for V=115 miles per hour and D=10 feet.

An analysis of results from tests with the spinner for propeller blade angles of 15°, 25°, and 35° indicated that the effect of the spinner could be translated into a drag value independent of the blade angle (5.5 pounds at 100 miles per hour). The results without the spinner were consequently corrected for the effect of the spinner by the formula

$$\Delta C_T=0.001075\ (V/nD)^2$$

instead of making additional tests with the spinner. Any errors incidental to this process are considered to be within the experimental error. This formula applies only to the conditions of the present tests.

The spinner was regarded as a part of the body; the reduction in drag of 5.5 pounds at 100 miles per hour was therefore primarily due to enclosing the hub portions of the propeller.

RESULTS AND DISCUSSION

The results are reduced to the usual coefficients of thrust, power, and propulsive efficiency defined as

$$C_T=\frac{\text{effective thrust}}{\rho n^2D^4}=\frac{T-\Delta D}{\rho n^2D^4}$$

$$C_P=\frac{\text{engine power}}{\rho n^3D^5}$$

$$\eta=\frac{C_T}{C_P}\frac{V}{nD}$$

where

T, tension in propeller shaft, pounds.
ΔD, change in body drag due to slipstream, pounds.
ρ, mass density of the air, slugs per cubic foot.
n, propeller speed, r. p. s.
D, propeller diameter, feet.
V, air speed, feet per second.

Charts for selecting or designing propellers are given in the form of C_s against η and V/nD,

$$C_s=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$$

Lines of constant thrust coefficient have been superposed on the power-coefficient curves to facilitate thrust computations at all air speeds for fixed-pitch and controllable propellers. For an outline of the methods, see reference 3.

The test results are given in the form of charts in figures 6 to 17. These results have also been tabulated

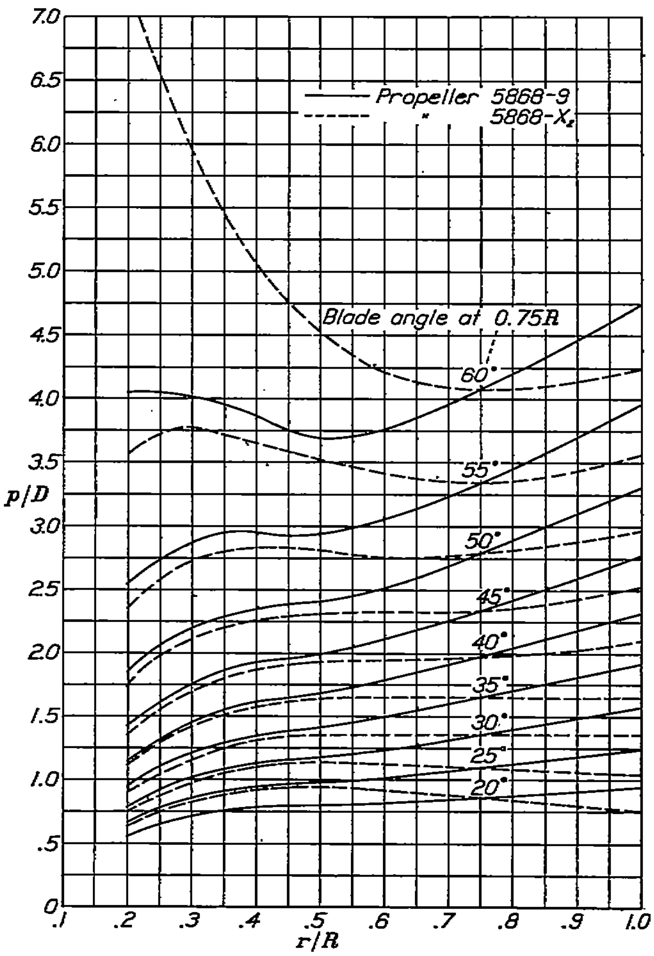

FIGURE 5.—Comparison of pitch distribution of propellers 5868-9 and 5868-X_2.

in three tables that are issued as a supplement to this report.

Propeller 5868–9.—There is nothing unusual about the characteristics of propeller 5868–9 without the spinner for the blade angles above 45°, that is, for the extended range of the tests. The efficiency envelope reaches a maximum efficiency value of about 86 percent at a blade-angle setting of about 30°. (See fig. 18.) For higher angles, the efficiency drops progressively to 77 percent for the 60° setting.

The take-off criterion for a controllable propeller, taken as the efficiency at 25 percent of the design speed, reaches a maximum value at a design C_s of 2.4, which

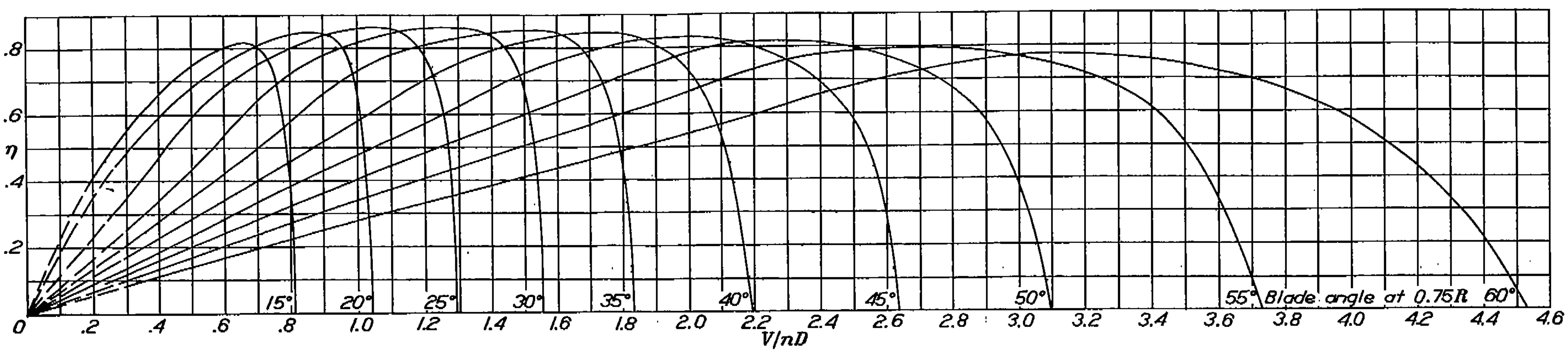

FIGURE 6.—Efficiency curves for propeller 5868-9.

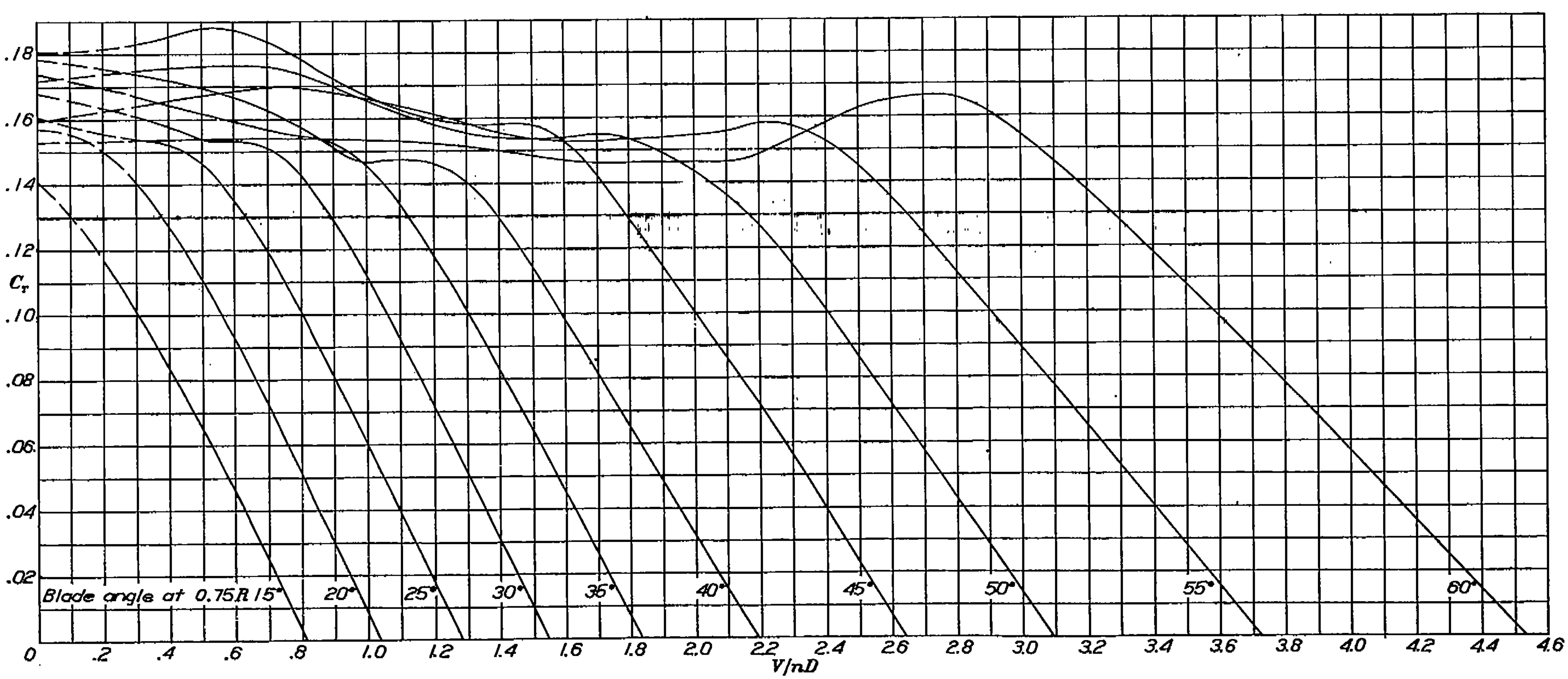

FIGURE 7.—Thrust-coefficient curves for propeller 5868-9.

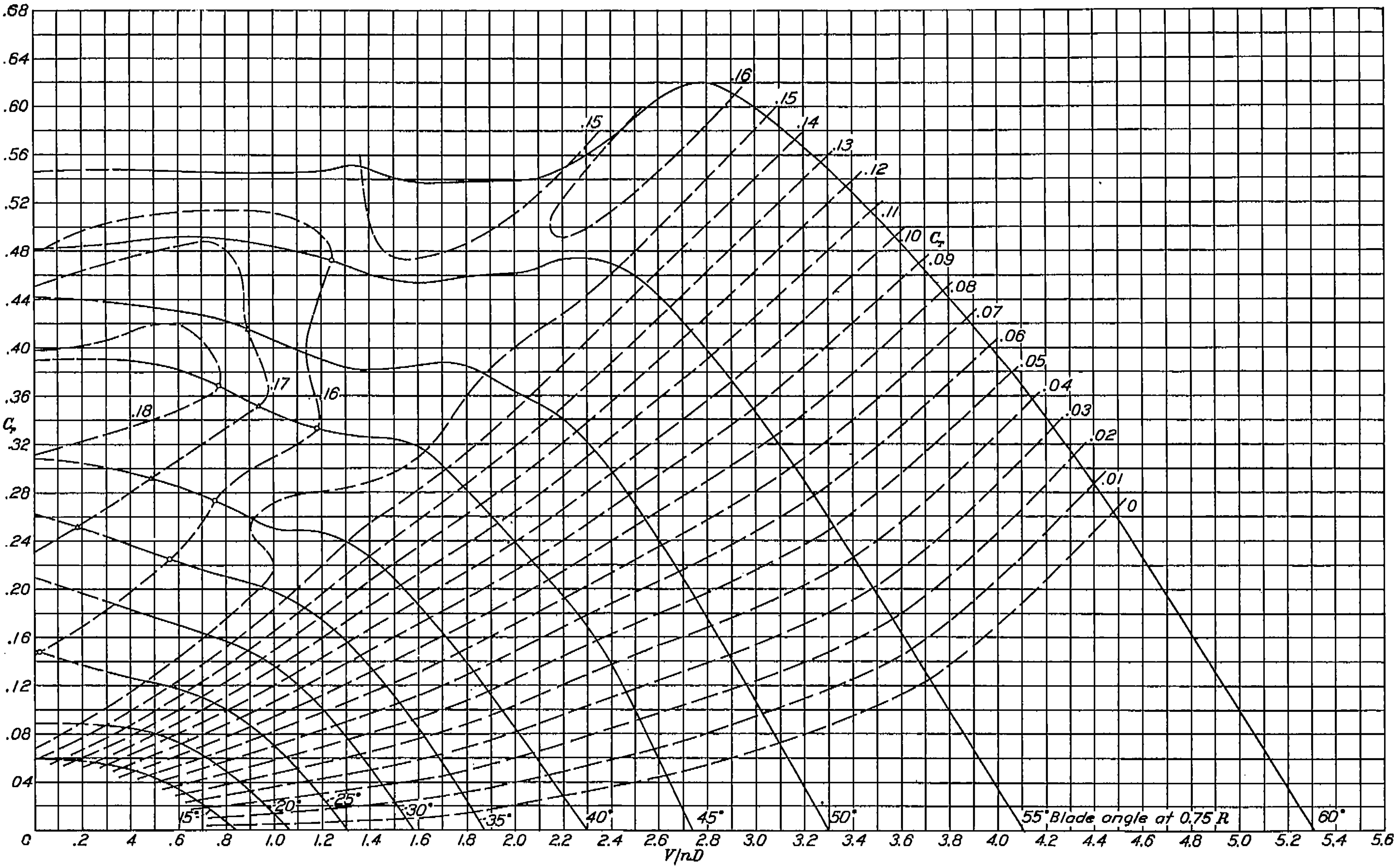

FIGURE 8.—Power-coefficient curves for propeller 5868-9.

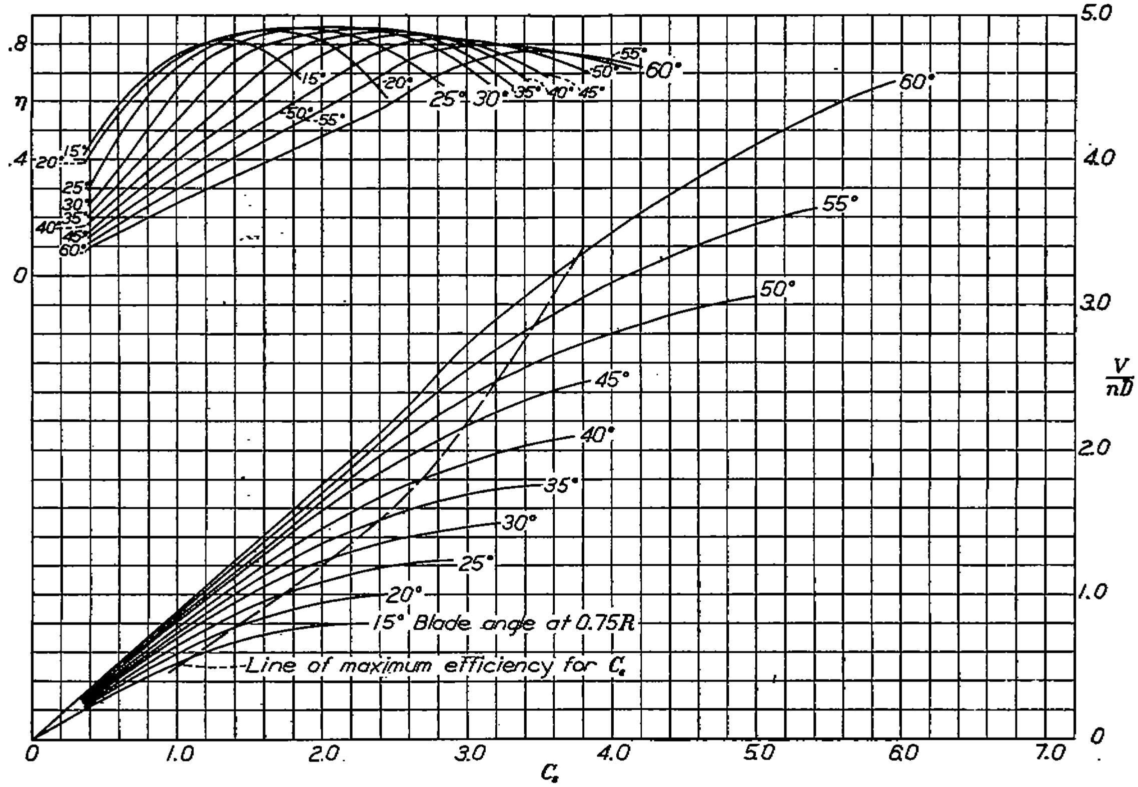

FIGURE 9.—Design chart for propeller 5868-9.

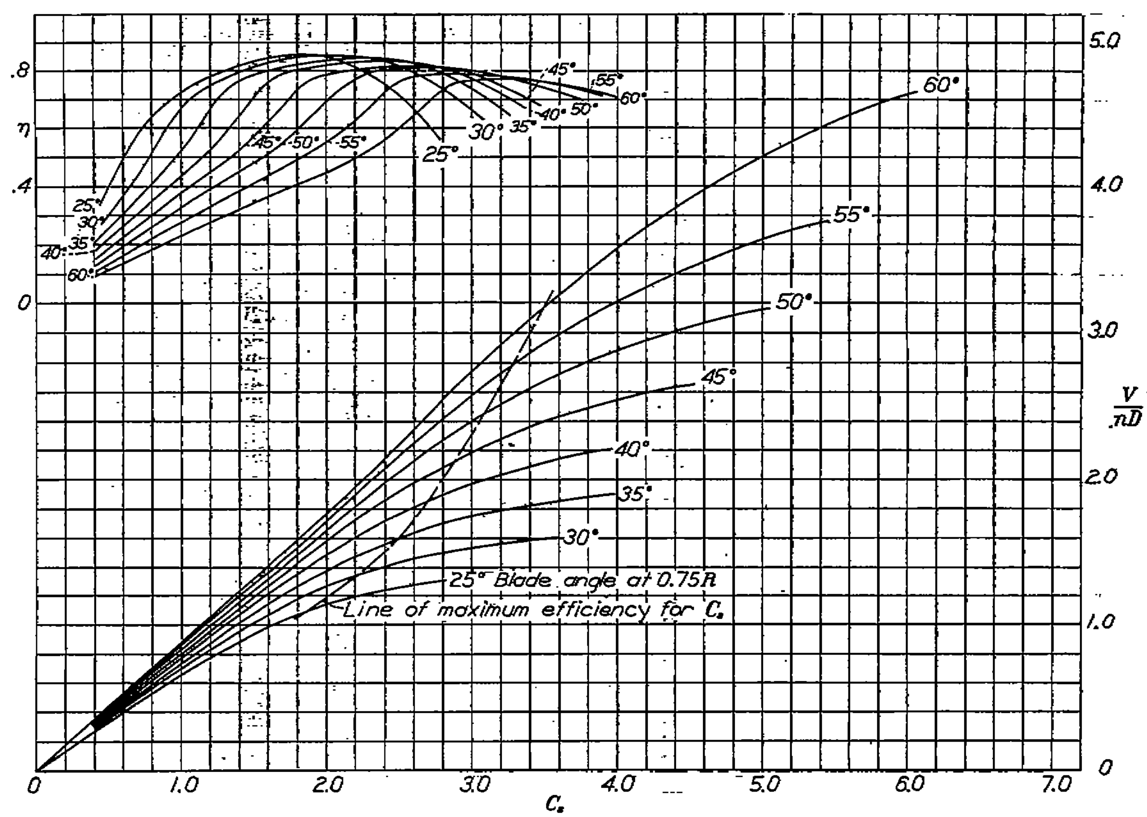

FIGURE 10.—Design chart for propeller 5868-X_3.

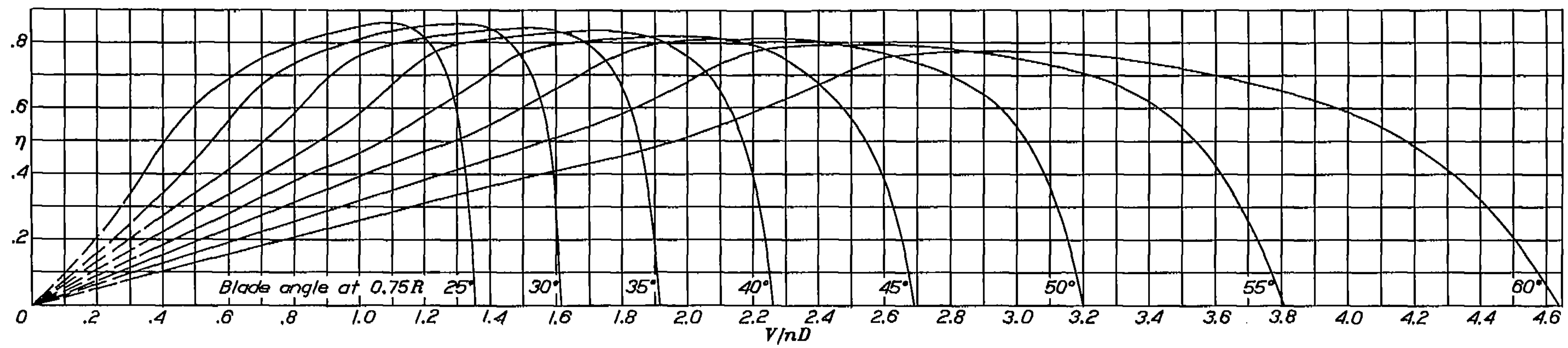

FIGURE 11.—Efficiency curves for propeller 5868-X$_3$.

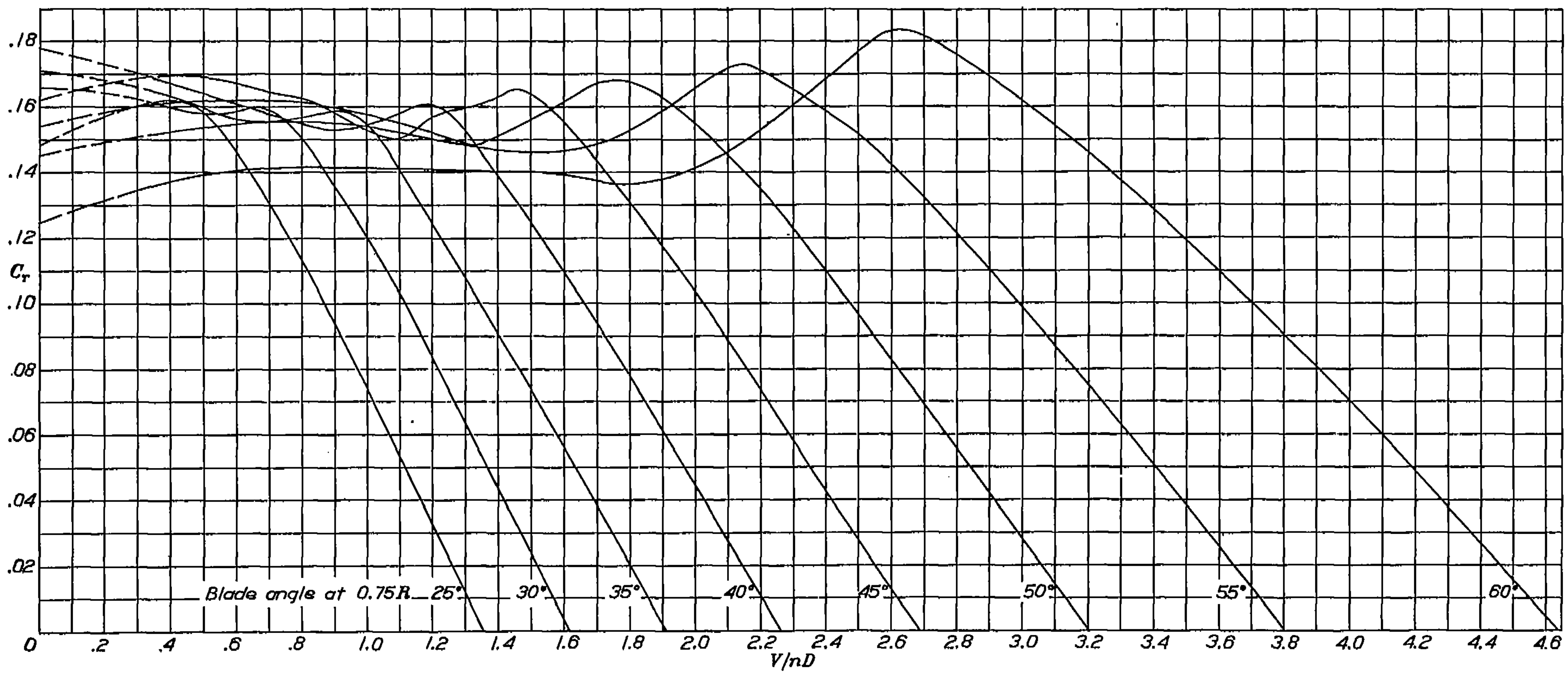

FIGURE 12.—Thrust-coefficient curves for propeller 5868-X$_3$.

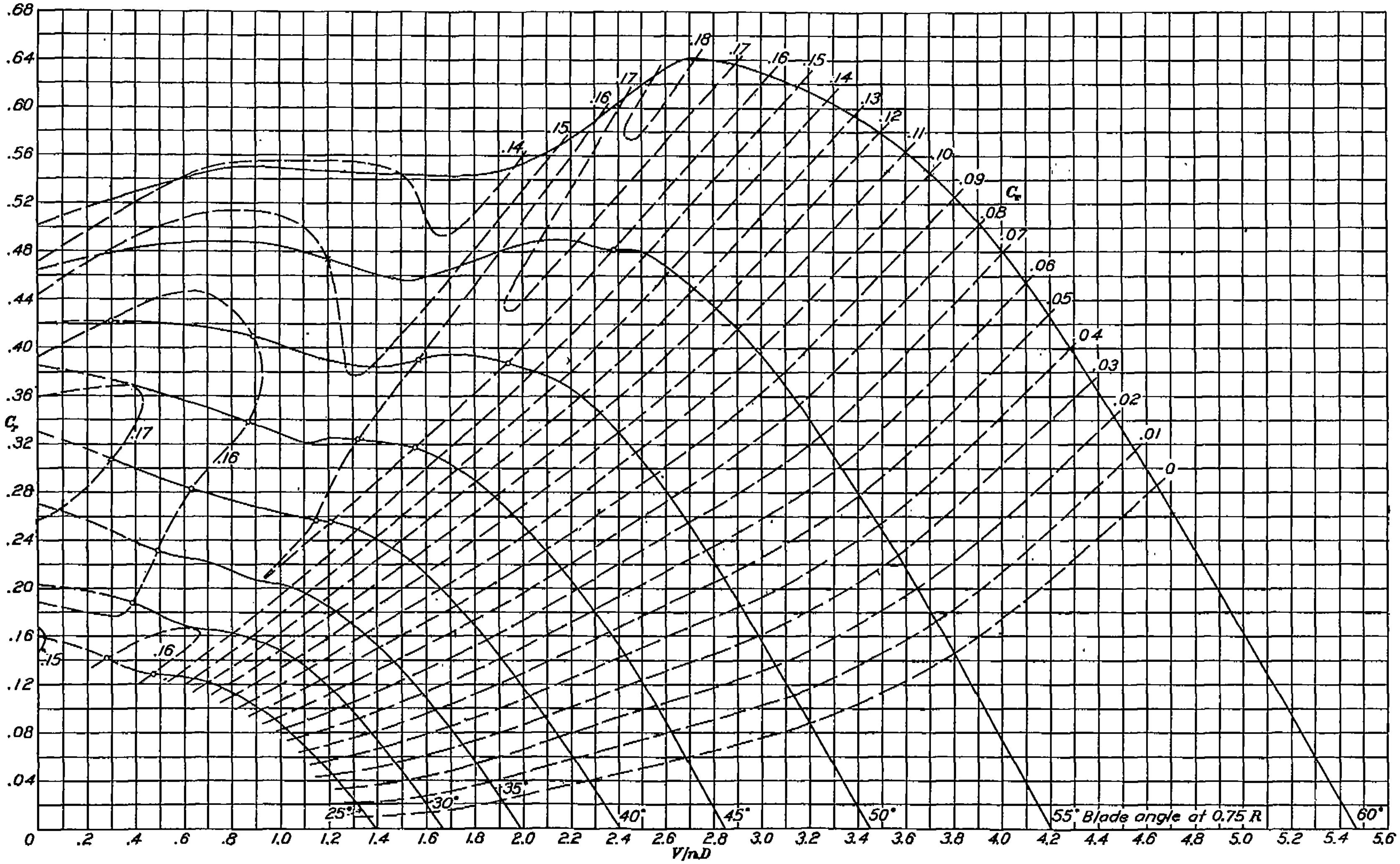

FIGURE 18.—Power-coefficient curves for propeller 5868-X_3.

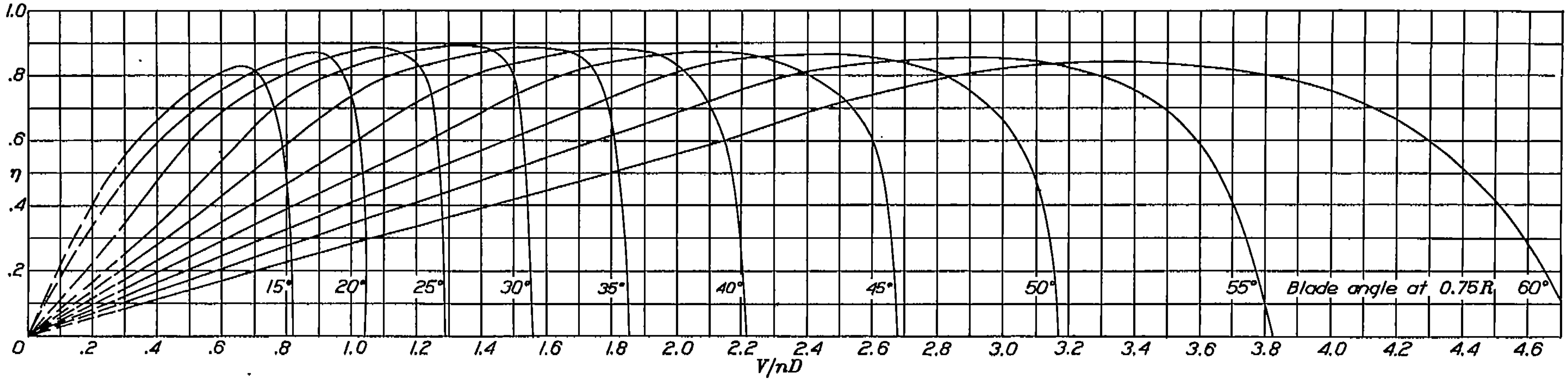

FIGURE 14.—Efficiency curves for propeller 5868-9 with spinner.

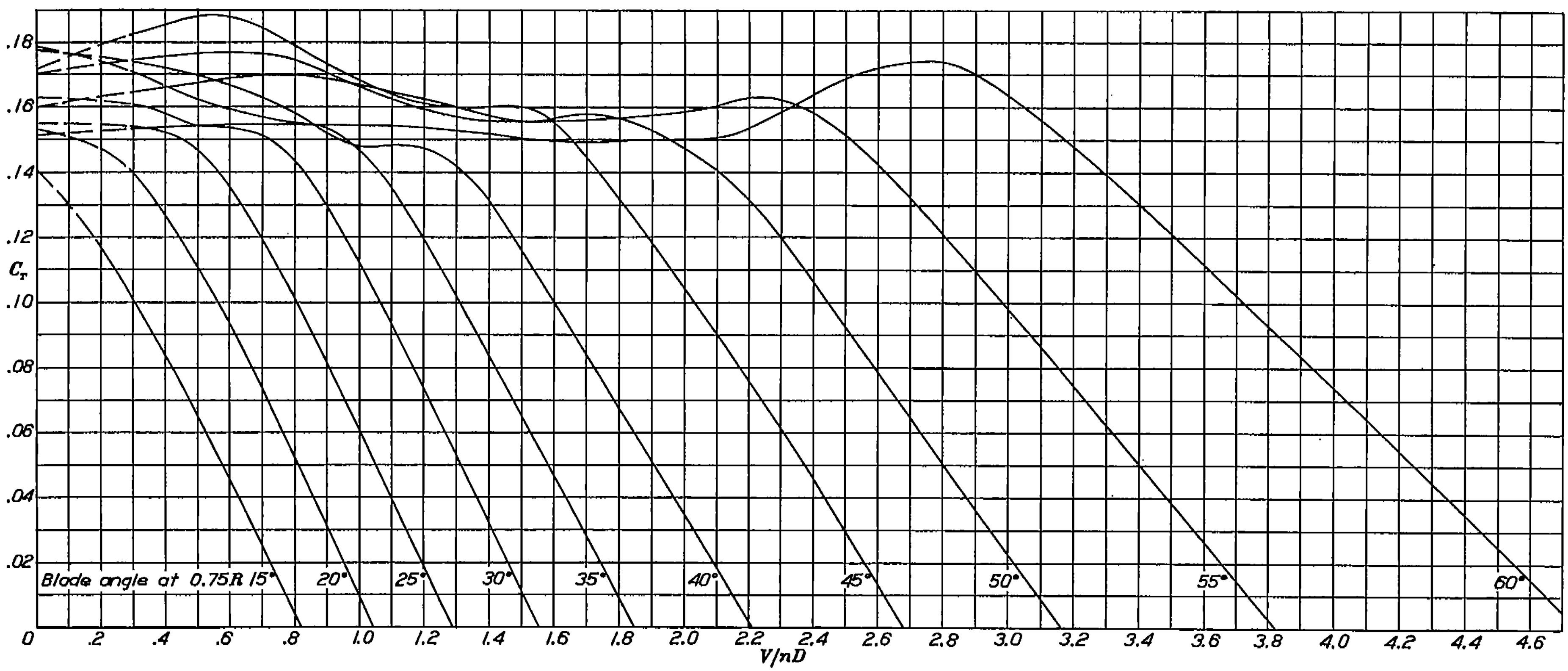

FIGURE 15.—Thrust-coefficient curves for propeller 5868-9 with spinner.

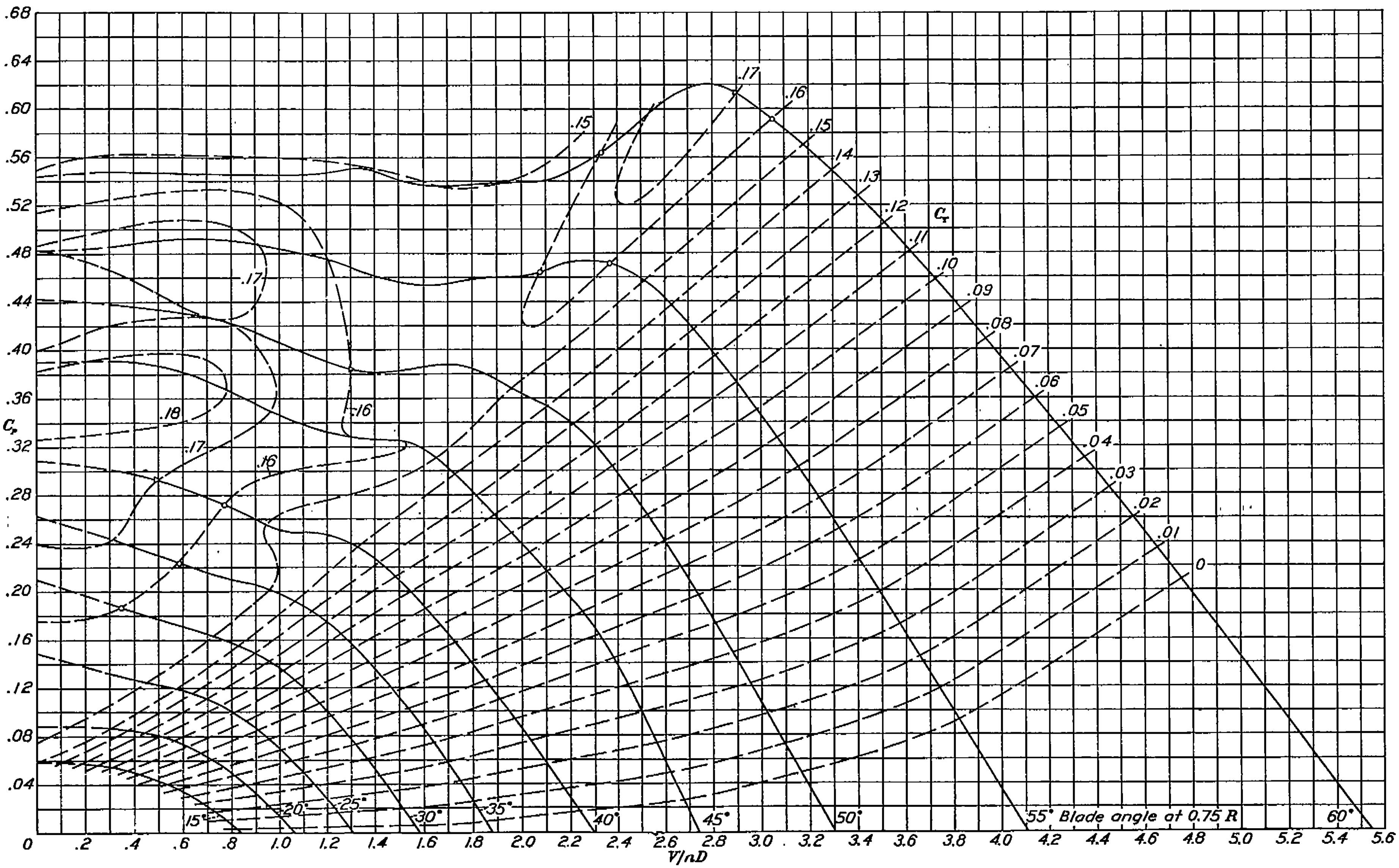

FIGURE 16.—Power-coefficient curves for propeller 5868-9 with spinner.

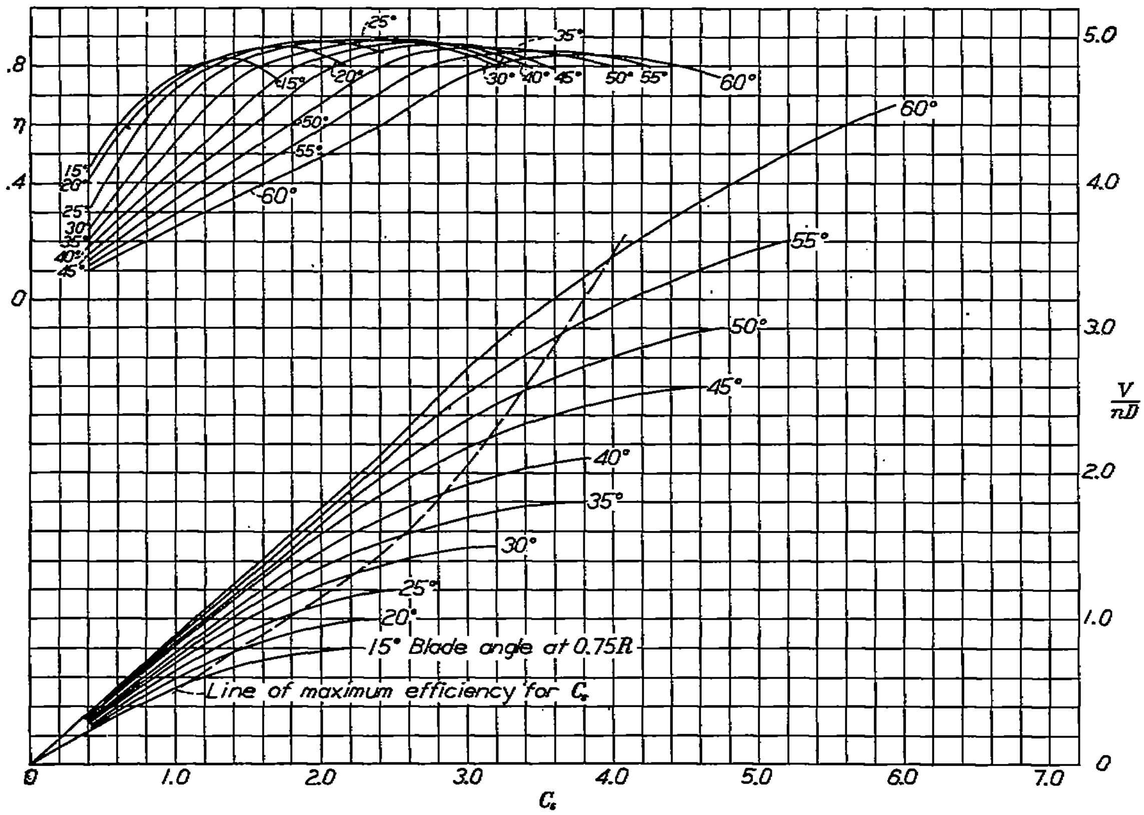

FIGURE 17.—Design chart for propeller 5868-9 with spinner.

corresponds to a blade-angle setting of 35° for the high-speed condition. It may be noted that the take-off setting is about 23°, a condition at which the blades are on the verge of stalling. The take-off efficiency drops with increasing design C_s chiefly because of the higher drag coefficients of the blade sections associated with angles of attack beyond the stall. An obvious method of reducing the take-off blade angle and yet absorbing the power is to increase the diameter, termed a "compromise" design because the high-speed efficiency suffers slightly.

A spinner is very beneficial for propeller-body combinations with liquid-cooled engine nacelles, particularly for conditions of high speed or high blade angle. A gain of about 8 percent in propulsive efficiency for a C_s value of 3.8 (approximately 60° blade angle) is obtained with the spinner and a lesser amount for lower blade angles (fig. 18). The use of the spinner raises the optimum design blade angle slightly and flattens the envelope of the efficiency curves to the extent that the efficiency remains relatively high for all angles up to 60°. Spinners are more advantageous for high speeds because the drag of the hub portions of the blades (5.5 pounds at 100 miles per hour) is a higher percentage of the thrust than for low speeds.

Propeller 5868–X_2.—When the blades of adjustable or controllable propellers are set at angles above that for nearly constant pitch distribution (15° for propeller 5868–9), the geometric pitch of the tip sections increases at a more rapid rate than for the shank sections up to some blade angle, depending upon the amount of twist in the blades. Beyond this angle the pitch of the shank sections increases at a more rapid rate, as may be seen from the relation

$$p = D\pi \frac{r}{R} \tan \beta$$

where β is the blade angle for any section. As the value of β for the tip section is always smaller than that for a shank section by the amount of blade twist present, the difference in the tangents of the two angles becomes greater in proportion to the differences in radii as the blade angle at $0.75R$ is increased. For propeller 5868–9, the rate of increase in pitch of the 0.2-radius section exceeds the rate for the tip section at blade angles, at $0.75R$, greater than 50°. (See fig. 5.)

Although pitch distribution has only a small effect on propeller characteristics, it would appear that some improvement is possible, particularly for high blade angles. The present attempt to improve the propulsive efficiency through different pitch distributions has thus far been unsuccessful, chiefly because the results for only one propeller (5868–X_2) are available.

The envelopes of the efficiency curves for propellers 5868–9 and 5868–X_2 are shown in figure 18. The small loss in efficiency of propeller 5868–X_2 as compared with that for propeller 5868–9 throughout the range investigated is attributed to the difference in pitch distribution. The optimum blade angle for nearly constant

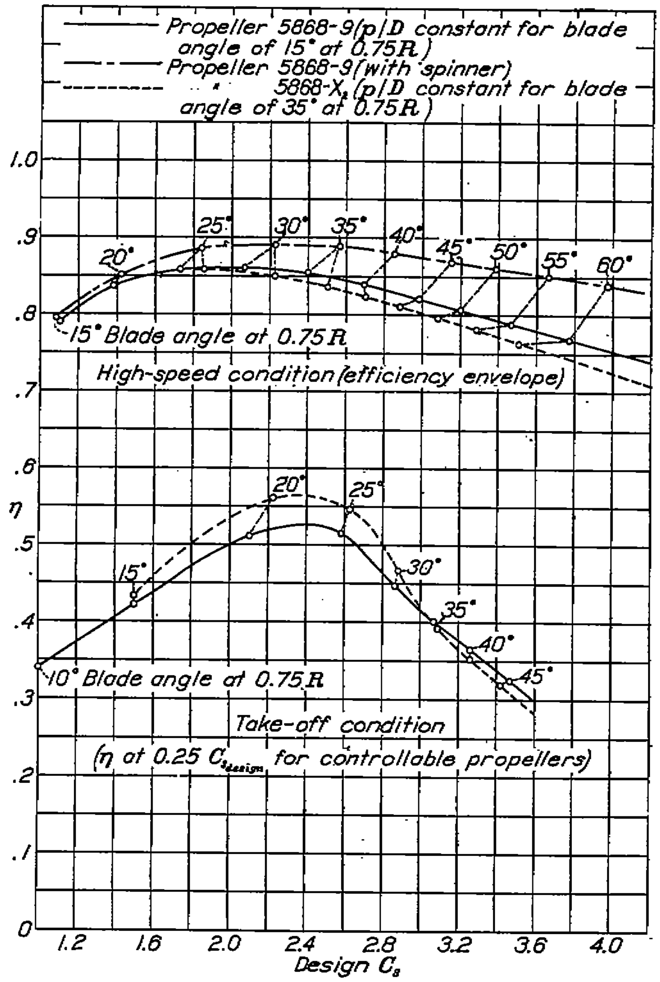

FIGURE 18.—Comparison of propellers having different pitch distributions and the effect of a spinner on the high-speed efficiency of the propeller.

pitch is evidently less than 35° for the conditions investigated. Some model tests made at Wright Field (reference 4) in which no body was mentioned indicated that the blade angle for constant pitch should lie between 22° and 34°.

The efficiency for the take-off conditions shows a gain for propeller 5868–X_2 over that for propeller 5868–9 for design C_s values up to about 3.0; beyond this value there is a small loss. The reasons for this condition are apparent in figures 19 and 20, wherein a comparison is made of the propeller characteristics for three effective pitch-diameter ratios for zero thrust. It may be noted that propeller 5868–X_2 does not stall so soon with increasing angle of attack (decreasing V/nD) as does propeller 5868–9, which accounts for the gain in efficiency. The efficiency computed for the take-off criterion is taken at a value of V/nD of one-fourth that for high speed. Propeller 5868–X_2 consequently has a higher take-off efficiency for conditions where the V/nD for stall coincides with the take-off criterion V/nD and has a lower efficiency when the values do not coincide. The delayed and abrupt stalling characteristic noted for propeller 5868–X_2 is evidently due to the fact that more of the blade elements stall at the same time than for propeller 5868–9.

Limitations and application of the test data.—In view of the fact that the present tests were run at relatively low tip and tunnel speeds, the effect of compressibility, which enters the problem at higher speeds, should not be forgotten. It is pointed out in reference 5 that corrections to the propeller characteristics for the take-off condition should be made for tip speeds above about 0.5 the speed of sound.

Earlier tests (reference 6) had indicated that no appreciable loss in efficiency was evident at tip speeds below about 0.9 the speed of sound for the high-speed condition. Later evidence shows that this value applies only to forward speeds up to 200 or 300 miles per hour. Figure 21 is a plot of the true speeds of each propeller section for a true tip speed of 1,000 feet per second (approximately 0.9 the speed of sound at sea level) and for different flight speeds. The curve of the section speeds corresponding to the compressibility stall was computed from airfoil data given in references 7 and 8 and from other high-speed airfoil data not published. An arbitrary correction for three-dimensional flow was made for the tip sections to bring the airfoil and the propeller data into agreement at the tip. Such a correction is justifiable on the grounds that induced velocities are reduced for three-dimensional flow.

Figure 21 indicates that, for air speeds above 300 miles per hour, sections at both the hub and the tips will be operating beyond the compressibility stall, assuming that the airfoil data as plotted apply to propellers, and that, at 500 miles per hour, all but a small part of the propeller will be operating beyond the critical speed. Losses at the tips may be avoided by reducing the tip speed, and losses at the hub sections may be avoided either by using a large spinner or by enclosing the blade shanks in cuffs of greater fineness ratio than the shanks themselves. The hub sections of a propeller operating in front of a radial engine are shielded by the cowling, an arrangement that produces about the same effect as a spinner. For very high-speed airplanes, it probably would be advisable to design the blade shanks to meet the conditions imposed by compressibility and to use airfoil sections having a higher critical speed than the Clark Y section, such as the N. A. C. A. 2400–34 series.

Another factor limiting the tip speed is the diminishing speed of sound with temperature at increased altitude. From figure 22, the probable upper limits in the application of the present data may be estimated for different altitudes. Although 500 miles per hour seems to be about the upper limit at sea level, neglecting tip and shank effects, that limit is reduced to about 425 miles per hour at 35,000 feet.

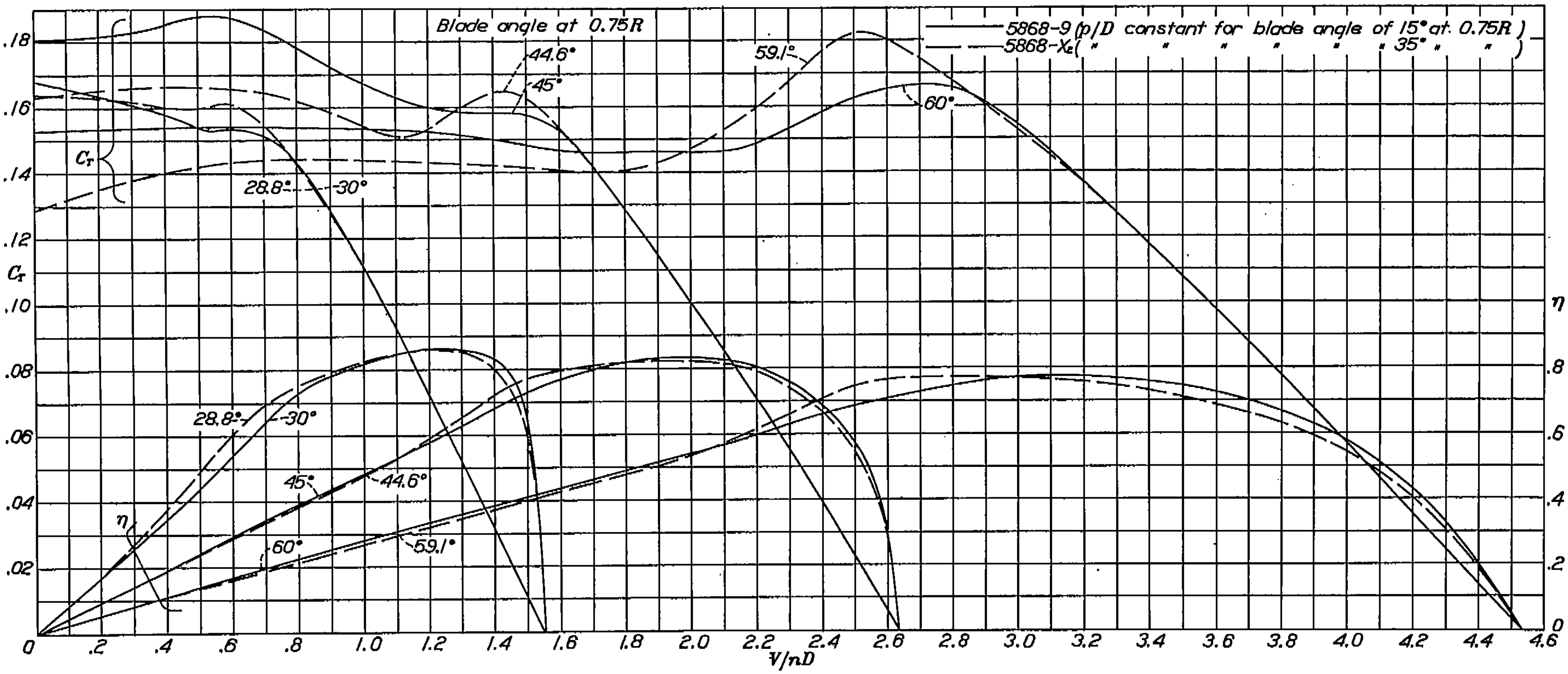

Figure 19.—Comparison of thrust and efficiency curves for propellers having two pitch distributions.

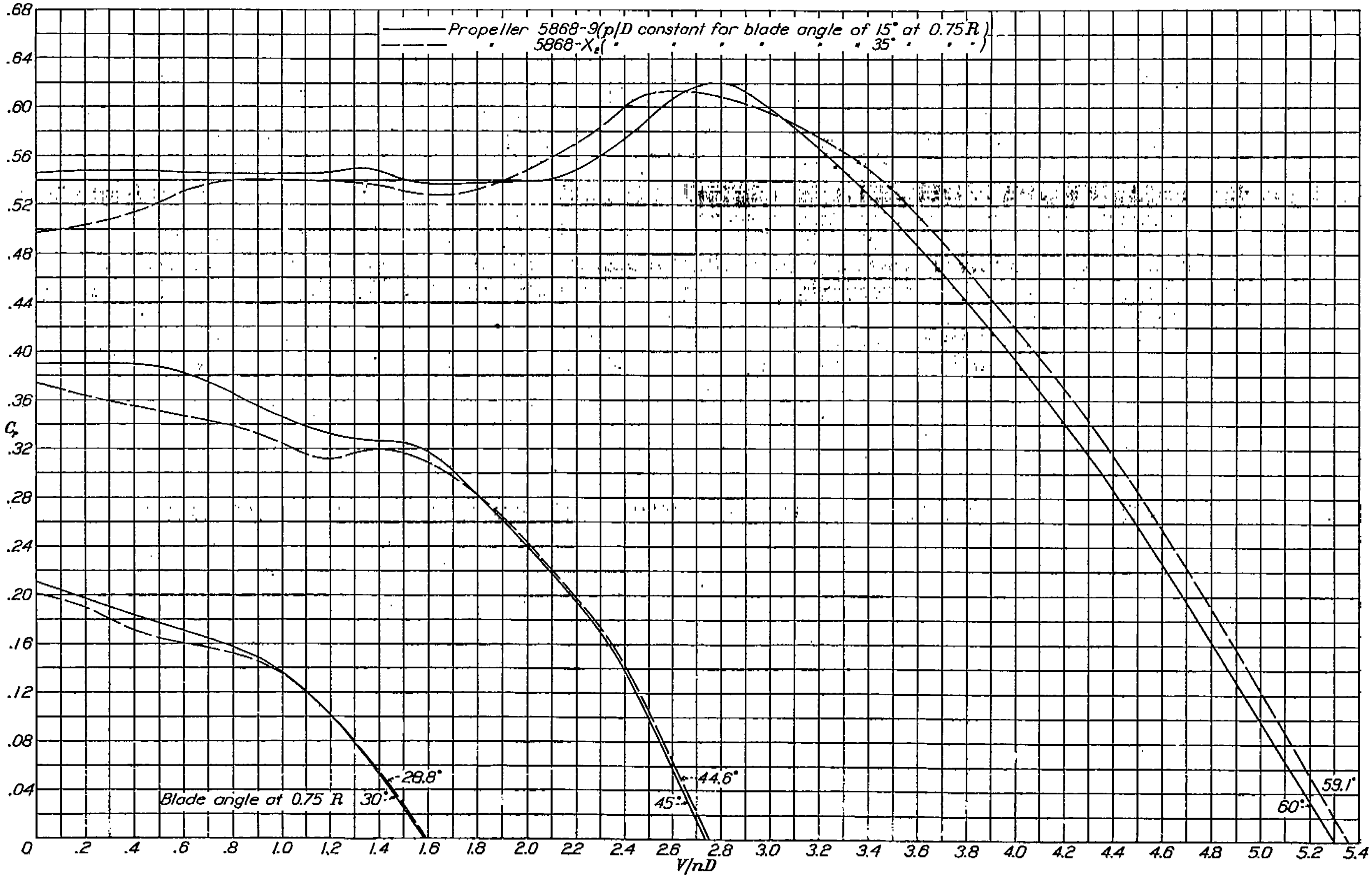

FIGURE 20.—Comparison of power curves for propellers having two pitch distributions.

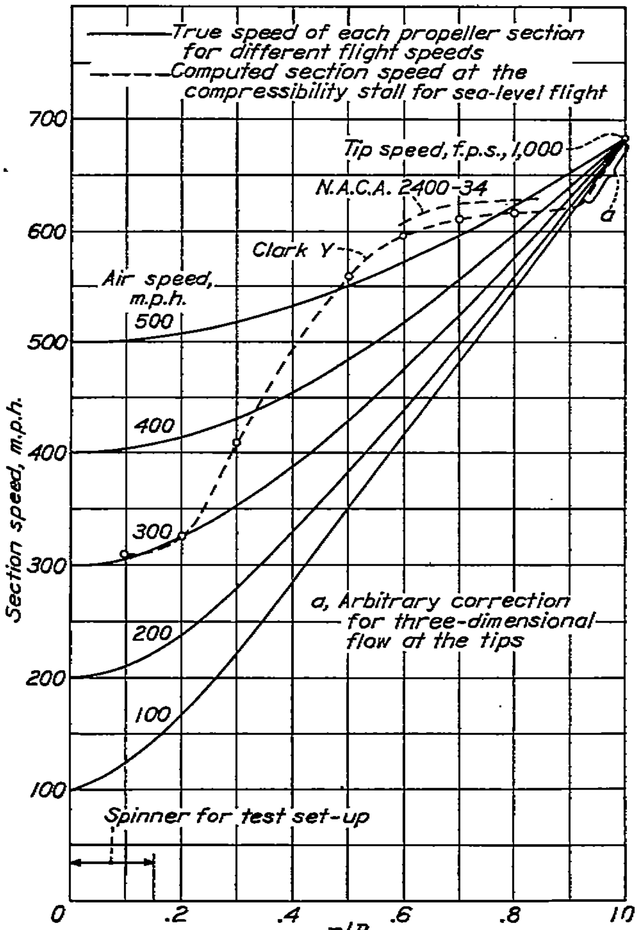

FIGURE 21.—Curves showing true speeds of propeller sections for a tip speed of 1,000 f. p. s. and different flight speeds; also computed section speeds at the compressibility stall.

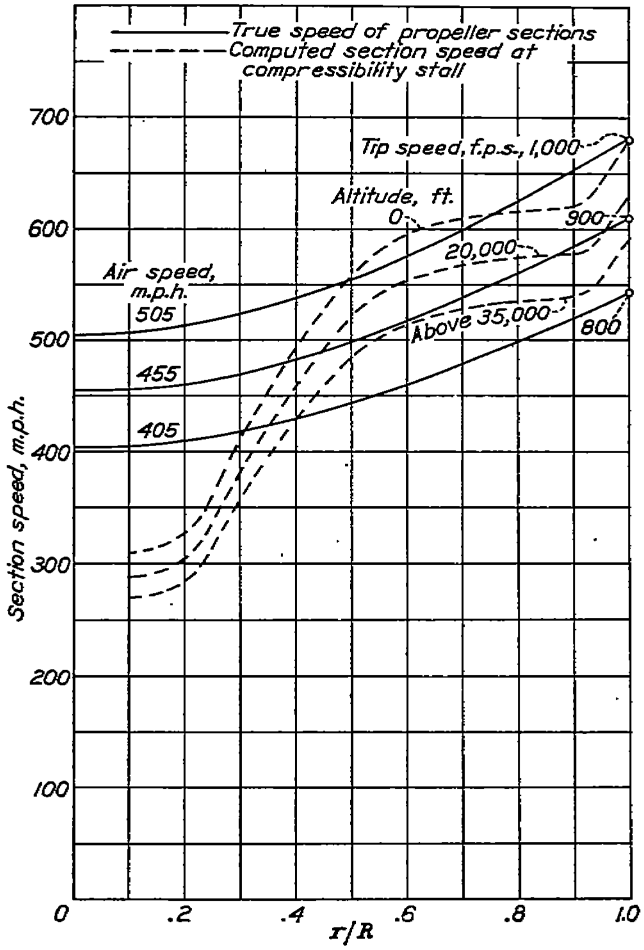

FIGURE 22.—Blade-section speeds corresponding to high-speed operation at 60° blade angle, and computed section critical speeds for different altitudes. Propeller 5868-9 with spinner.

CONCLUSIONS

The propulsive efficiency at a blade angle of 60° was about 9 percent less than the maximum value of 86 percent, which occurred at a blade angle of about 30°. The efficiency at a blade angle of 60° was increased about 7 percent by correcting for the effect of a spinner and at a blade angle of 30°, about 3 percent.

An attempt to improve the propulsive efficiency of propellers set at high blade angles by reducing the geometric pitch of the tip sections with respect to the shank sections (namely, increasing the blade angle for nearly constant pitch distribution from 15° to 35°) resulted in a small loss in the high-speed efficiency and a gain in the take-off efficiency for low blade angles.

The blade-angle range covered in this report is applicable to flight conditions up to about 500 miles per hour at sea level and about 425 miles per hour at 35,000 feet, provided that compressibility effects at the blade tips and shanks do not become critical.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *April 14, 1938.*

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